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CRACK INITIATION AND PROPAGATION IN NOTCHED FATIGUE SPECIMENS

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ABSTRACT

An approximate analysis has been developed whereby the number of cycles required to start an "engineering size" crack and the number of cycles required to propagate this crack to failure could be estimated for a notched specimen from a knowledge of the fatigue behavior of unnotched specimens. Cracks are assumed to occur at the root of a notch in a number of cycles dependent only on the localized surface strain and then propagate in a manner similar to those in an unnotched specimen. Reasonably good predictions of crack initiation, crack propagation, and total life were obtained for annealed 4340 steel and 7075 T6 aluminum notched specimens and stress concentration factors of 2 and 3.

Author

INTRODUCTION

The fatigue life of any structure or specimen having a discontinuity or notch may be considered to be composed of three separate stages. These stages are (1) the initiation of a crack at the root of the notch, which is dependent on the local stress and strain at the notch root, (2) the propagation of the crack through the material, and finally (3) the fracture of the structure or specimen that occurs when the remaining cross-sectional area together with the localized stress concentration at the tip of the fatigue crack cannot sustain the applied load. Unless these three stages are separated and individually evaluated, the influence of the various testing variables becomes beclouded.

The stage of the fatigue process that has received the least attention from an engineering viewpoint is that of crack initiation. Although many fundamental studies have been made by such investigators as Forsythe[1], Wood[2], and numerous others[3], the engineering significance of microcracks observed under high magnification early in the fatigue life of specimens by these investigators is not clear. It has been suggested (e.g. refs. 4 and 5) that the fatigue process be divided into two stages, crack initiation and crack propagation. However, no definite criterion was suggested to establish when a fatigue crack is of sufficient size to demarkate separation between crack initiation and propagation from an engineering point of view. One of the present authors in a recent report[6] has suggested a simple formula for estimating the number of cycles required to initiate a crack in an unnotched specimen. While this proposal has not yet received adequate engineering evaluation, and further studies are obviously required before it can be accepted, it does provide a definite formulation for the number of cycles required to produce a crack of "engineering size." For this reason it can be extremely useful in the notch problem.

In order to predict when fatigue crack initiation will occur, the local strain at the notch root must first be determined. The strain analysis at the root of a notch is extremely complicated and even in the elastic range has been determined only approximately. However, within the limits of experimental accuracy, the stresses and strains in the elastic range can be determined by classical methods. [7,8] Relatively little work has been done to establish the stress and strain distribution in the plastic range. Two interesting proposals have been made, one by Stowell as modified by Hardrath and Ohman[9] and the other by Neuber.[10] These methods provide approximations whereby the stresses and strains at the root of a notch may be determined from the knowledge of the elastic stress concentration factor and the stress-strain curve of the material. While their validity has not been extensively evaluated experimentally for either monotonic or cyclic loading both of these methods provide a simple means whereby this aspect of the fatigue problem can be made tractable.

Crack propagation has been studied rather extensively in recent years. Most of these studies have dealt with cracks in thin sheet under loads pulsating from zero to a maximum value. Many fatigue specimens, however, are not of this configuration. For example, the most extensively investigated configuration for low cycle fatigue is an hour-glass shape specimen of circular cross section having a minimum diameter of approximately 1/4 in. Boettner, Laird, and McEvily[11] have made a limited study of crack propagation in this type of specimen. Their results, together with the results of other studies are discussed in a companion lecture presented at this conference.[12]

This present report presents the results of an exploratory study developed to permit a simple analysis of the fatigue process in hour-glass specimens with simple machined notches subjected to uniaxial reversed loading. The study is limited to and presents preliminary results for the estimation of crack initiation and propagation to failure for two materials, annealed 4340 steel and 7075 T6 aluminum. The investigation was conducted to determine the degree of validity that could be expected when highly simplified assumptions were made with regard to three major facets of the fatigue problem of notches specimens: (a) the determination of the strain at the root of the notch, (b) the number of cycles required to develop a crack of "engineering size," and (c) the number of cycles to propagate the crack of "engineering size" to complete fracture.

ANALYTICAL METHOD

The method to be used in analyzing notched specimens is shown schematically in figure 1. The total strain range $\Delta\epsilon$ is plotted against the number of cycles to produce either initial cracking N_0 or final failure N_f. The failure curve FD represents the fatigue characteristic of the material based on uniaxial push-pull of smooth 1/4-in. hour-glass shaped specimens, determined either experimentally or by analytical prediction according to the method of reference 6 (modified in ref. 12). The curve EBC represents the life to initiate a crack[12] and is related to the number of cycles to produce fracture by

$$N_o = N_f - 4N_f^{0.6} \tag{1}$$

Suppose a specimen with a notch is strain cycled so that the nominal uniform strain range is $\Delta\epsilon_1$. If the strain concentration factor is K_ϵ, the localized strain range at the root of the notch is $K_\epsilon \cdot \Delta\epsilon_1 = \Delta\epsilon_2$. It will be assumed that the crack will be initiated in a number of cycles dependent only on the localized strain range at the root of the notch. Thus, for a strain range $\Delta\epsilon_2$ the number of cycles to initiate the crack will be AB, designated N_o.

Once the crack has started, it will be assumed to propagate in a manner similar to the propagation that would have occurred if the crack had started in a smooth specimen (absence of the notch). Thus, once the crack has begun and grown in a notch to a sufficient depth such that the strain field at the crack tip is no longer significantly affected by the initial notch geometry, the number of cycles to failure will be approximately the same as that to propagate a crack to failure in a smooth specimen at the strain range $\Delta\epsilon_1$. This range of cycles is shown by the line CD and designated ΔN. The total life of the notched specimen considered, therefore, is the sum of AB and CD.

Strictly speaking, a transfer period between the crack initiation phase AB and the crack propagation phase CD must be considered. This compromise is accomplished in the present analysis by defining N_o, not as the number of cycles to form a microcrack, but rather as the number of cycles to form an engineering size crack according to equation (1). While it is recognized that the simplification assumed here may be highly questionable, the results associated with the assumption will be compared with the experiments to ascertain its validity.

Examination of figure 1 reveals at once a limitation to the concept outlined for a material that displays a distinct knee in the fatigue curve. If such a material is cycled at a nominal strain range below the knee, the crack propagation period CD becomes indeterminate because it lies below the range where the initiation and propagation curves are defined. It is well known, however, that once a crack is started at the root of a stress concentration, this crack can propagate at a nominal applied strain range below the fatigue limit of a smooth specimen. A modification of the procedure is required for treatment of this case, but this modification is considered beyond the scope of the present paper.

The data used to arrive at equation (1)[12] were obtained from materials that had reductions in area greater than 30 percent and that were sufficiently notch-ductile to permit appreciable crack growth stages. For very low ductility or highly notch-sensitive materials, such that the critical crack depth for fracture hardly exceeded the initial notch depth, equation (1) would not be valid since crack growth could not take place and therefore crack initiation and failure would occur at approximately the same number of cycles. Modifications to the proposed method to permit the prediction of the notch fatigue life of notch brittle materials will be discussed in a companion lecture.[12] The method outlined in this paper should therefore be limited to the prediction of the notch fatigue life of materials sufficiently notch insensitive to exhibit reasonable crack growth stages.

EXPERIMENTAL PROCEDURE

The procedure and equipment used for this investigation were essentially the same as those used previously by the authors in evaluating the fatigue behavior of smooth specimens and are described in detail in reference 13. Additional equipment was required to observe the initiation of cracks at roots of notches during testing. A modification was also made to the method of strain cycling since the extensometers described in reference 13 would have interferred with the visual observation of the notches.

Method of Strain Cycling

The procedure used to strain cycle smooth specimens was to maintain a constant diametral strain range by altering the applied stress range as necessary during the test. Materials that strain harden under cyclic loading require a progressive increase in stress range while cyclic strain softening materials require a progressive decrease in stress range. For each smooth (unnotched) specimen tested a record was kept of stress range necessary to maintain a constant strain range as a function of the number of cycles. A more complete description of this procedure and sample curves of stress range against cycles for various materials are reported in reference 13.

In order to strain cycle notched specimens without the aid of extensometers, use was made of the data of stress range against cycles previously obtained from smooth specimens. The stress range against cycle history that had been obtained by strain cycling the smooth specimen was then duplicated in the notched specimen. It was then assumed that the nominal strain range in the notched specimen was equal to that of the smooth specimen that produced the loading history being followed.

Method of Detecting Crack Initiation

The optical system used for the detection of cracks is shown in figure 2. Two microscopes (A) with continuously variable (ZOOM) magnification ranging from 7 to 30 were mounted on opposite ends of extension arm (B) in such a way that the centerlines of the microscopes and the two notches on the specimen (C) coincided. The microscopes were independently focused from knobs (D), and the notch roots could be examined from any angle by simply rotating the whole assembly about the lower loading rod (E). The notch configurations used will be described in the next section.

Crack initiation was defined as the number of cycles required to produce a crack of "engineering size" which was the crack length associated with the previously discussed compromise. Once a detectable crack was developed at the root of a notch, its surface length increased to approximately 0.01 in. within a negligible percentage of the total crack propagation stage. Therefore, the point of initiation was taken at a crack length ranging from 0.006 to 0.010 in.

DETERMINATION OF LOCAL STRAIN AT NOTCH ROOT

In order to obtain the number of cycles for crack initiation from equation (1) it is first necessary to estimate the strain concentration at the notch root. As already indicated, the process is complicated by plasticity, and no general solution has as yet been found. Several simplified approaches are, however, available which for the present will be assumed adequate for the treatment of this problem. It will be seen in a later section that a high degree of accuracy in this phase of the analysis is not essential because only the crack initiation period is influenced by the results of the computation, and in many cases involving notched specimens, this initial period is relatively short compared with the total life of the part.

Figure 3 shows the notch configurations that were used for experimental purposes in this investigation. The specimen used had a conventional circular hour-glass shape with a minimum diameter of 1/4 in. Slot notches were machined into the specimens as shown in the figure. Two geometries were used having radii of 0.008 and 0.025 inch for which the elastic stress concentration factors K_e were 3 and 2, respectively. The computations to determine K_e were made by two methods. In the first, the assumption was made that the notch was machined entirely around the specimen, thus producing a configuration as treated by Peterson.[8] In the second method of computation, the assumption was made that the specimen was square and that the notches were machined across only two of the opposite faces having the same notch dimensions as those given in figure 3. This configuration is also treated by Peterson in reference 8. Both methods of determining K_e agreed sufficiently to conclude that the theoretical stress concentration factors were approximately 3 and 2 as shown in the table in figure 3. These approximate values of K_e were used to proportion the specimens. The analysis to follow uses measured values of fatigue notch factors in place of approximate stress concentration factors.

The fatigue notch factors K_f were determined experimentally by dividing the stress which resulted in failure of a smooth specimen in 10^6 cycles by that which resulted in the same life in the notched specimen. Approximately the same fatigue notch factors were obtained by using stress rati   at other values of high lives greater than 10^5 cycles. The measured valu   sed on a life of 10^6 cycles are tabulated in figure 3. For the elastic stress concentration factor K_e of 3 both 7075 T6 aluminum and annealed 4340 steel produced fatigue notch factors of 2.9. For the elastic stress concentration factor of 2 the annealed 4340 steel produced a notch fatigue factor of 2, but the 7075 T6 aluminum gave a notch fatigue factor of only 1.7. Whether this discrepancy is due to basic material behavior or to some factor associated with the testing procedure was not established.

The elastic stress concentration factors shown in figure 3 are valid when the strain at the root of the notch is very near or below the elastic limit. When larger strains are imposed, resulting in plasticity at the root of the notch, the stress and strain concentration factors cannot be determined according to the elastic analysis of Peterson.[8] Two alternative methods, one based on an equation derived by Stowell[9] and the other on an equation derived by Neuber[10], were used in the present investigation to determine the plastic strain concentration factor K_ϵ in terms of the plastic stress concentration factor K_σ and either the elastic stress concentration factor K_e or the fatigue notch factor K_f. In this investigation, since the fatigue notch factor was experimentally determined, it was used in the analysis. When this factor is not available, the analysis described in the following paragraphs may be conducted with K_e.

The first method is based on a proposal of Stowell modified to a more general form by Hardrath and Ohman.[9]

$$K_\sigma = 1 + (K_f - 1)\frac{E_2}{E_1} \qquad (2)$$

Equation (2) gives the stress concentration factor K_σ in terms of the fatigue notch factor K_f and two quantities E_1 and E_2. These quantities are secant moduli on the stress-strain curve of the material (fig. 4). The term E_1 refers to the secant modulus at point 1 on the curve, where point 1 represents the nominal condition in the cross section of the notched specimen. For purposes of illustration, E_1 was chosen to be on the elastic portion of the stress-strain curve, but it could also be in the region of plasticity. E_2 is the secant modulus at point 2 which supposedly represents the true condition at the root of the notch, when the actual stress and strain concentration that develops as a result of notch geometry are taken into account. The location of point 1 is known, hence E_1 is known. The value of K_f depends only on the notch geometry and is therefore also known. Equation (2) can be solved iteratively for K_ϵ and E_2 from a knowledge of the stress-strain curve.[14,15] However, it is possible to derive a graphical procedure which eliminates the need for a trial-and-error solution. Equation (2) may be rewritten by using the definitions of E_1 and E_2 (fig. 4) to yield

$$E_1 = \sigma_1/\epsilon_1 \tag{3}$$

and

$$E_2 = \sigma_2/\epsilon_2 \tag{4}$$

Then

$$K_\sigma = 1 + (K_f - 1)\frac{\sigma_2/\sigma_1}{\epsilon_2/\epsilon_1} \tag{5}$$

or

$$K_\sigma = 1 + (K_f - 1)\frac{K_\sigma}{K_\epsilon} \tag{6}$$

Finally

$$K_\sigma = \frac{K_\epsilon}{K_\epsilon - K_f + 1} \tag{7}$$

Equation (7) relates the stress concentration factor at the root of the notch to the strain concentration factor and to the fatigue notch factor. A universal auxiliary diagram (fig. 5) can be used in the solution of this equation. The solid lines in figure 5 are representations of K_σ against K_ϵ for selected values of K_f according to equation (7). The solid diagonal line is the elastic line where $K_\sigma = K_\epsilon = K_f$. Since $K_\epsilon = \epsilon_2/\epsilon_1$ and $K_\sigma = \sigma_2/\sigma_1$, a curve can also be plotted in figure 5 which is derived from the stress-strain curve of the material. The dot-dash line in figure 5 is obtained by dividing the values of stress and strain at a number of selected values of point 2 (σ_2 and ϵ_2) by the known nominal values of stress and strain at point 1 (σ_1 and ϵ_1) and plotting the resulting stress ratio against the strain ratio. The intersection of this normalized stress-strain curve with the curves for the appropriate fatigue notch factor constitutes the solution of equation (7). The intersections for $K_f = 2$ and $K_f = 3$ are shown as points A and B in figure 5.

An alternative approach is based on a suggestion of Neuber.[10] In his investigation Neuber considered the case of a specimen subjected to shear and concluded that as the stress concentration factor is reduced by plasticity at the root of a discontinuity, the strain concentration factor is increased, so that the product of stress and strain concentration factors remain approximately constant. Since initially the condition is completely elastic, both the stress and strain concentration factors are equal to K_f; therefore the product must remain K_f^2.

$$K_\sigma \cdot K_\epsilon = K_f^2 \tag{8}$$

The solution of equation (8) in association with the actual stress-strain curve of the material can also be facilitated by a plot shown in figure 5. Here the dotted curves represent the hyperbolas required by plots of K_σ against K_ϵ according to equation (8). Again the dot-dash curve is the relation between K_σ and K_ϵ for the test material normalized to the nominal conditions in the test section. The intersection of the dotted curves and the dot-dash curve constitutes the solution of equation (8). For illustrative purposes they are shown in figure 5 as points A' and B'.

While neither Neuber nor Stowell, Hardrath, and Ohman proposed the use of their respective relations for computations under cyclic loading, it seems reasonable that if the methods are to be used at all, the cyclic stress-strain curve[6] should be used in the analysis rather than the stress-strain curve obtained under monotonic loading. The cyclic stress-strain curves for the two materials tested and analyzed in the present investigation are shown in figure 6.

Figure 7 shows the two nominal stress concentration factors used and the results of computations by equations (7) and (8) to determine the strain concentration factors K_ϵ at the root of the notch for each of the two materials. Figure 7(a) shows the results for 7075 T6 aluminum; figure 7(b) the results for annealed 4340 steel. For nominal strains below the elastic limit both methods obviously produce the same results equal to the fatigue notch factors. As the nominal strain across the section is increased the strain concentration factor becomes greater than the fatigue notch factor. The two methods do not completely agree regarding the determination of the strain concentration factor; however, as already noted, the results of the life computations were not significantly altered by these differences. An example of the method of determining the strain concentration factor is given in the appendix.

COMPUTATION OF CRACK INITIATION

As discussed in reference 6 and modified in reference 12, the number of cycles at which a crack of "engineering size" develops is given approximately by equation (1). For the two materials that were tested in the present investigation, no direct observations were made on the smooth specimens to determine the number of cycles required to initiate an "engineering size" crack. Therefore, for purposes of analysis, the number of cycles to produce a crack were computed from equation (1) by using the observed number of cycles to failure N_f. Figures 8 and 9 show the results of the computations for the two materials. In each plot, the solid line is a smooth curve through the data representing the life of unnotched specimens as a function of strain range. The dotted curve represents the number of cycles to initiate a crack, and the dot-dash curve the number required to propagate a crack to failure as functions of strain range of an unnotched specimen.

The number of cycles required to initiate a crack in the presence of the stress concentration were determined by using the strain concentration factors from figure 7 and the value of the applied axial strain range. Multiplying the applied nominal strain range by the strain concentration factor gave the local strain range at the root of the notch. Using this strain range in conjunction with figures 8 or 9 established the number of cycles to initiate the crack in the presence of the strain concentration.

The results are shown in figures 10 and 11 for the two materials evaluated. Only the computations making use of the Neuber prediction for strain concentration factor are shown here; the computations based on the Stowell-Hardrath-Ohman analysis gave results that differed inappreciably. The dotted curves in figures 10 and 11 represent the predictions for the fatigue notch factors of 1.7 for the 7075 T6 aluminum and 2.0 for the annealed 4340 steel. The dot-dash curves represent the predictions for the fatigue notch factors of 2.9 for both materials. The circles show the experimental results for the smaller fatigue notch factors and the squares the results for the sharper notches with K_f equal to 2.9. Good agreement was obtained for both materials and for each of the notches evaluated. An example of the method of computation described above is given in the appendix.

COMPUTATION OF CRACK PROPAGATION

As already shown in figure 1, the crack propagation period for a given strain range depends to a first approximation on the applied strain range only and not on the strain concentration factor imposed; the crack propagates under a strain concentration factor essentially unrelated to the strain concentration which caused it to form. This strain concentration depends largely on the crack itself and not on the geometric conditions existing prior to the development of the crack. Thus, the prediction for the period of crack propagation is the same for both notch configurations investigated. These predictions are shown by the solid lines in figures 12 and 13. The experimental data agree well with the predictions for the 7075 T6 aluminum (fig. 12), and it will be seen that the measured period of crack propagation is almost identical for each of the two notch configurations investigated. For the annealed 4340 steel (fig. 13) the agreement is good at crack propagation lives above approximately 1000 cycles. Below this value, however, the experimental results are lower than the predictions. The measured values of ΔN are again almost the same for each of the two notch configurations investigated. An example of the method used to compute ΔN as described previously is also given in the appendix.

One possible reason why the predictions of ΔN are greater than those measured for the annealed 4340 steel in the low cyclic life region can be seen in figure 14, where a plot is shown of the strain softening characteristic of this material for a strain range of 0.022 on a smooth specimen. As in all strain cycling tests, it is necessary to change the stress range during the progressive cycling of the specimen in order to maintain constancy of strain range. The alloy 4340 steel is a strain softening material in which the stress to maintain a constant strain range is progressively decreased as cycles are accumulated. For the smooth specimen, the estimated number of cycles required to cause a crack to initiate is shown in figure 14 at about 800 cycles for a life to failure of approximately 1050 cycles. During the crack initiation stage, numerous cycles are therefore imposed for which the applied stress range is relatively low. Once the crack is formed, it will grow under the influence of this lower stress range. However, when the nominal strain range of 0.022 is imposed in the presence of a notch, the number of cycles to crack initiation is considerably lower, and the bulk of the specimen has not yet softened to the same stress level that a smooth specimen reaches at its time of crack initiation. Because of the strain softening characteristic of the material, the number of cycles to propagate a crack at high stress range might well be expected to be less than that predicted on the assumption that the stress range remains constant for a given strain range.[6] The analysis for 7075 T6 aluminum which does not strain soften but rather is moderately strain hardening does not show this characteristic discrepancy (fig. 12).

In making an analysis of the crack propagation period for materials that have already been investigated by studying smooth specimens of the same size, it is not necessary to consider the crack growth process in detail. Since the number of cycles to crack initiation is known from equation (1) and the number of cycles to failure is measured, the period of crack propagation is determined by simple subtraction. In more complicated cases, however, or when greater generality is sought, it is necessary to make a detailed examination of the equations governing crack growth and final fracture. Such analysis is beyond the scope of the present paper. It is touched on, however, in the companion lecture.[12]

COMPUTATION OF TOTAL LIFE

The total fatigue life of a notched specimen is the sum of the crack initiation period and the propagation period, (fig. 1). Thus, by the addition of the proper curves of figures 10, 11, 12, and 13 the total life can be predicted for each of the two notch configurations ($K_e = 2$ and 3) and for each material. The results are shown in figures 15 and 16 by the dotted and dot-dash curves, respectively. Again, the experimental results agree favorably with the predictions except for the very low cyclic lives in the case of the annealed 4340 steel, as already discussed.

Of special interest is the fact that both the analytical predictions as well as the experimental observations indicate that notches of nominal stress concentration factors of 3 do not have a much more detrimental effect on the cyclic life than do those having nominal stress concentration factors of 2. The reason for this can be seen by examination of figures 10, 11, 12, and 13. Even though the higher stress concentration factors have a considerable effect in reducing the crack initiation periods (this effect differing appreciably for the two notch configurations investigated) the crack initiation period is generally a relatively small part of the total life. The crack propagation period is assumed to be independent of the stress concentration factor of the notch and in most practical cases is the largest portion of the total life. Thus, only to a minor extent does the sum of the two components reflect the differences introduced by the higher nominal stress concentration.

This observation is in agreement with the general experimental finding that increasing the nominal stress concentration factor of a notch does not produce a correspondingly large decrease in fatigue life in the low cycle range. In fact, as the nominal stress concentration factor is increased, a value is reached beyond which further decrease in total life is negligible. In practice, fatigue notch factors greater than 7 are not encountered in conventional fatigue tests.[16]

An example of the method used to calculate the total life of a notched fatigue specimen is given in the appendix.

DISCUSSION

The method discussed is, of course, only an approximation. The assumption that the fatigue process of a notched specimen (apart from the question of final fracture) can be broken up into two distinct parts, the initiation period dependent on the strain concentration factor and the propagation period essentially independent of this factor, ignores the complex situation that truly exists during the transition period. A more detailed analysis would be desirable, but in view of the good agreement between analysis and experiment obtained through the simplifying assumptions, it may be questioned whether the complexity of a detailed analysis would be warranted by potentially small increases in accuracy.

The method illustrated is valid only for the prediction of the fatigue life of specimens containing notches when corresponding tests have been conducted on similar specimens devoid of notches. For more complex shapes which have not previously been analyzed in the absence of notches, a more detailed analysis would be required to determine the details of the crack growth process. For crack initiation, it may be assumed that this period is more or less independent of configuration depending largely on the local strain at the surface of the notch root. If no observations have been made directly to relate strain range with the number of cycles to produce crack initiation, use can be made of the relation between strain range and the number of cycles to produce failure in a 1/4-inch-diameter specimen, equation (1) being applied to determine crack initiation.

It is interesting to make a comparison between the method described herein and that previously used by other investigators to predict the fatigue life of notched specimens. Peterson,[14] for example, also used the concept of plastic strain concentration determined by the Stowell-Hardrath-Ohman approximation to obtain the strain at the root of a notch. He then utilized this strain range in conjunction with fatigue characteristics of smooth specimens to determine the life of the notched part. The strain range at the root of the notch was used in conjunction with the curve of strain range against life of the smooth specimen to predict life of the notched part. In essence, therefore, the strain concentration of the notch was applied to the entire life of the specimen, propagation as well as initiation. Applying the strain concentration to the propagation period obviously has the effect of producing more conservative calculations of life compared to the method discussed in this report. Figure 17 shows a comparison between calculations for 7075 T6 aluminum for nominal stress concentration factors of 3 and 5. The method of Peterson predicts large progressive decreases in life as the nominal stress concentration factor is increased. The method described in this report does not. As already seen in figures 15 and 16, changing from a stress concentration of 2 to 3 did not significantly reduce the life. Preliminary tests with a very sharp notch having a nominal stress concentration factor of approximately 4 also showed a relatively small reduction in life, as would be expected by noting figure 17. The approach used by Peterson would have predicted a much larger decrease than that observed.

Crews and Hardrath[15] have made the same assumption as Peterson regarding the use of the strain concentration factor. In their study they actually measured the stress and strain at the root of a notch and predicted notched specimen life from experiments in which stress across the unnotched specimen was equal to that measured at the root of the notch. Their predictions of life were considerably lower than were observed experimentally.[15] Again, the reason for this conservative result is probably that no separation was made between the initiation and the crack propagation phases. The strain concentration factors were essentially applied to both phases.

Both types of calculations, on the one hand giving full weight to the strain concentration at the root of the notch, and on the other hand entirely ignoring its effect during the propagation stage, represents extremes of approximation. It would appear, based on the results of this investigation, that the approximation involved in ignoring the effects of the notch during the propagation phase is the better compromise. It should be emphasized, however, that all of the preceding discussion relates only to materials that have sufficient ductility and are notch insensitive enough to exhibit reasonable crack growth stages.

CONCLUDING REMARKS

An approximate analysis has been developed whereby the number of cycles required to start an "engineering size" crack and the number of cycles required to propagate this crack to failure could be estimated for a notched specimen from a knowledge of the fatigue behavior of unnotched specimens. Reasonably good agreement with experimental results were obtained for the two materials and the two notch configurations tested. In the form presented, the method is presently limited to estimates of the fatigue life of notched specimens above the unnotched fatigue limit and to materials exhibiting a "reasonable" crack growth stage. Further evaluation with more materials and for a wider range of notch geometry is desirable. The effects of cyclic strain hardening or softening on the crack propagation stage also requires further evaluation.

APPENDIX - SAMPLE CALCULATIONS

The following calculations are for an annealed 4340 steel notched fatigue specimen with an elastic stress concentration factor of 2 subjected to an axial strain range of 0.008. For this material and notch configuration, the fatigue notch factor had been measured and was found to be equal to the elastic stress concentration factor, namely 2. The following calculations are made by using this value of K_f. For cases where K_f is not known, the value of K_e can be assumed to be equal to K_f.

Determination of Strain Concentration Factor K_ϵ at Notch Root

For a nominal applied strain range $\Delta\epsilon_1$ of 0.008, the nominal stress range is found from the cyclic stress-strain curve of figure 6(b) to be 123 ksi. It should be noted that for this example, the nominal values are slightly into the plastic region of the cyclic stress-strain curve. The cyclic stress-strain curve is now normalized for these nominal values by choosing a number of points on this curve and dividing the stress ranges at these points by 123 ksi and the strain ranges by 0.008. This normalized cyclic stress-strain curve is the dot-dash curve plotted in figure 5.

The strain concentration factors K_ϵ determined from the methods of both Neuber and Stowell-Hardrath-Ohman are now read off figure 5 at the intersection of the K_f lines and the normalized cyclic stress-strain curve. The Neuber method results in a $K_\epsilon = 3.0$, while the Stowell-Hardrath-Ohman method gives $K_\epsilon = 3.5$. These values are plotted in figure 7(b) for the nominal strain range of 0.008.

Determination of Number of Cycles to Initiate Crack N_o

The strain range at the root of the notch is equal to the nominal strain range multiplied by the strain concentration factor. For this example the value of K_ϵ determined from the method of Neuber will be used; therefore, $\Delta\epsilon_2 = 0.008 \times 3.0 = 0.024$. The number of cycles to initiate a crack in this notched specimen is assumed to be the same number of cycles required to initiate a crack in an unnotched specimen subjected to a strain range equal to 0.024. The value of N_o is therefore read off figure 9 for the strain range 0.024 and is equal to 380 cycles. This value is plotted in figure 11 at the nominal strain range 0.008.

Determination of Number of Cycles to Propagate Crack to Failure ΔN

The nominal strain range for the notched specimen is the same as the nominal strain range for the unnotched specimen and, since the notch is assumed to have no influence on the propagation stage ΔN for the notched specimen, is equal to ΔN for the unnotched specimen. This value is read off figure 9 for the nominal strain range 0.008 and is equal to 1150 cycles. This value is plotted in figure 13 again at the nominal strain range.

Determination of Total Life N_f

The total life of the specimen used in this example is the sum of the number of cycles predicted to initiate the crack and the number of cycles predicted to propagate this crack to failure. For this case then, $N_f = 380 + 1150 = 1530$ cycles and is plotted in figure 16, once again at the nominal strain range.

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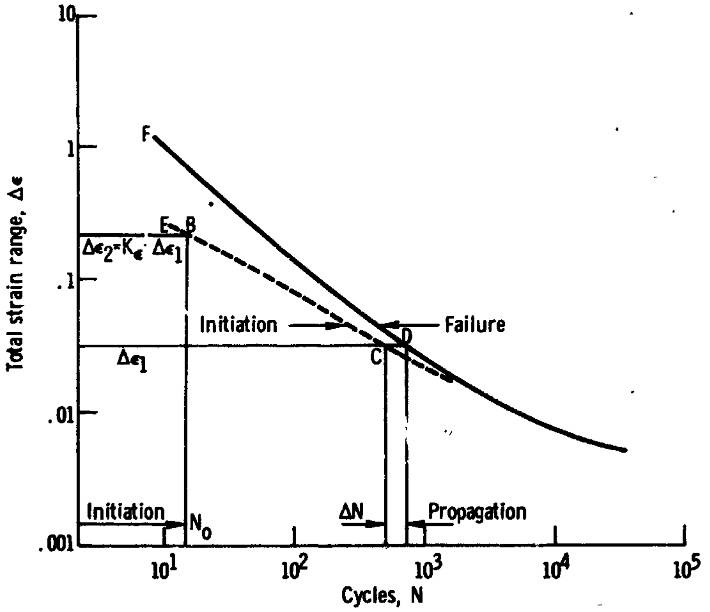

Figure 1. - Total fatigue life as sum of initiation and propagation components.

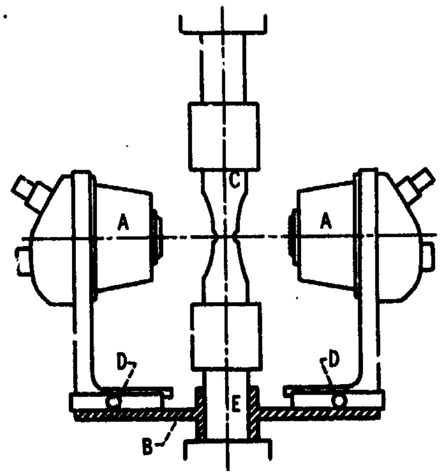

Figure 2. - Test setup for measurement of cracks at root of notched fatigue specimens.

Material	R	D	K_e (calc.)	K_f (meas.)
7075 T6 aluminum	0.008 in.	0.010 in.	3	2.9
7075 T6 aluminum	0.025 in.	0.010 in.	2	1.7
4340 steel (annealed)	0.008 in.	0.010 in.	3	2.9
4340 steel (annealed)	0.025 in.	0.010 in.	2	2.0

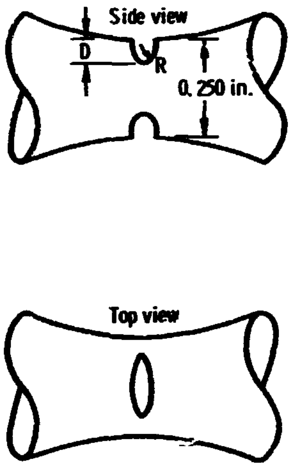

Figure 3. - Fatigue notch configuration used in this investigation.

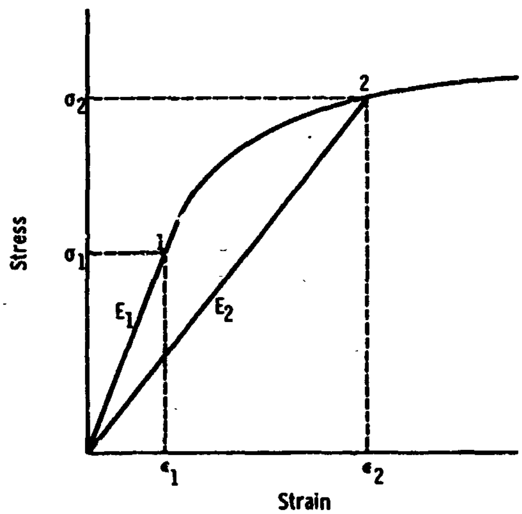

Figure 4. - Schematic stress-strain curve to illustrate terminology in equation (2).

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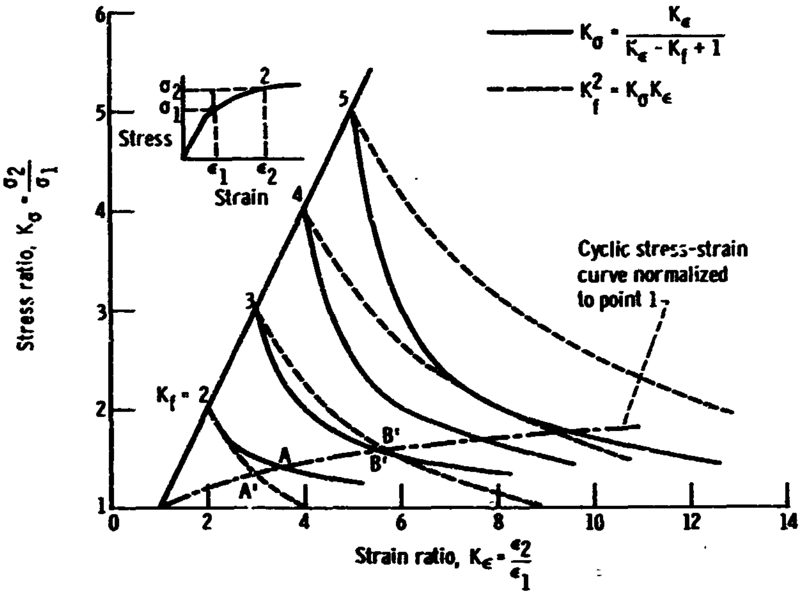
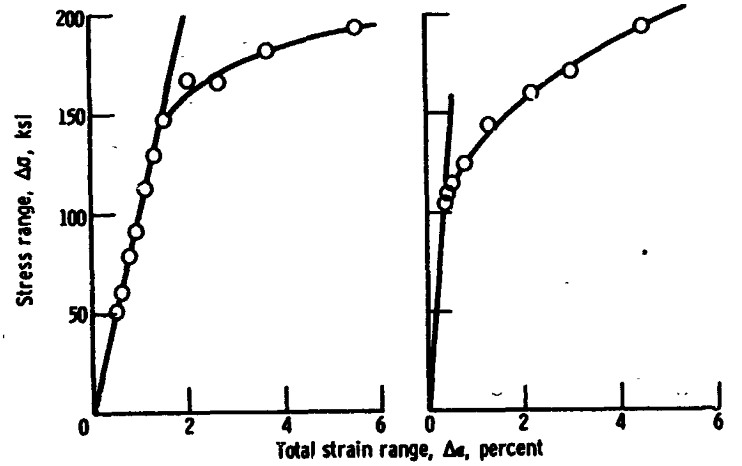
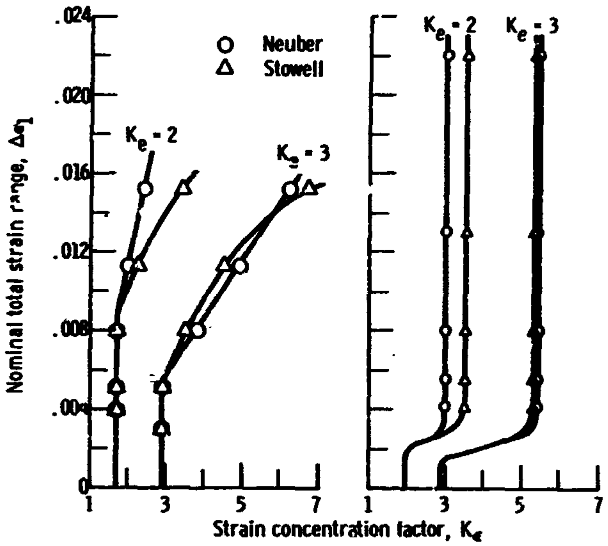


Figure 5. - Graphical determination of plastic stress and strain concentration factors.



(a) 7075 T6 aluminum. (b) Annealed AISI 4340 steel.

Figure 6. - Cyclic stress-strain behavior for reversed axial strain cycling.



(a) 7075 T6 aluminum. (b) Annealed AISI 4340 steel.

Figure 7. - Variation of strain concentration factor at root of notch as function of nominal applied strain range.

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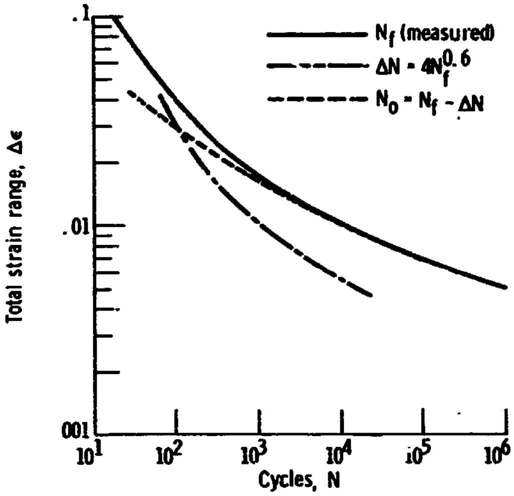

Figure 8. - Initiation, propagation, and failure curves for 7075 T6 aluminum.

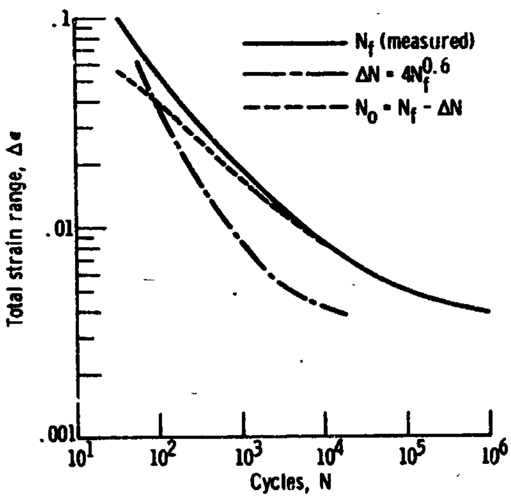

Figure 9. - Initiation, propagation, and failure curves for annealed AISI 4340 steel.

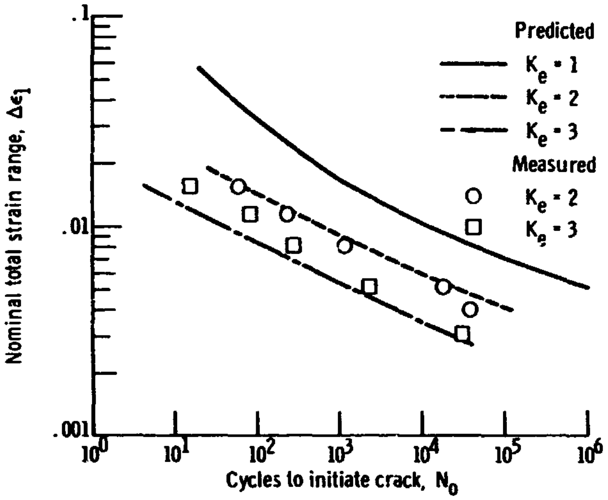

Figure 10. - Crack initiation of notched 7075 T6 aluminum.

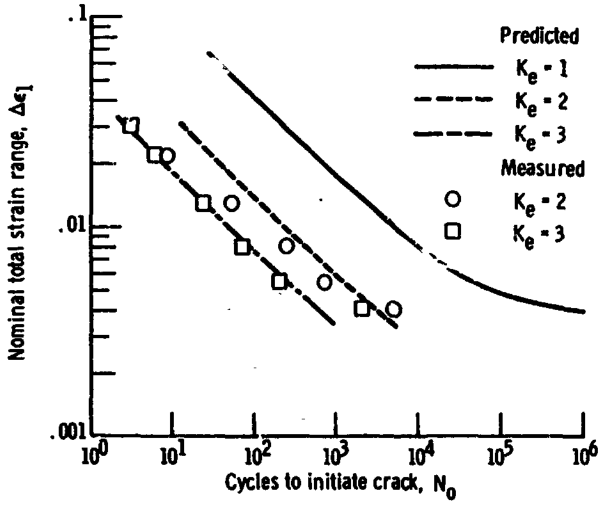

Figure 11. - Crack initiation of annealed AISI 4340 steel.

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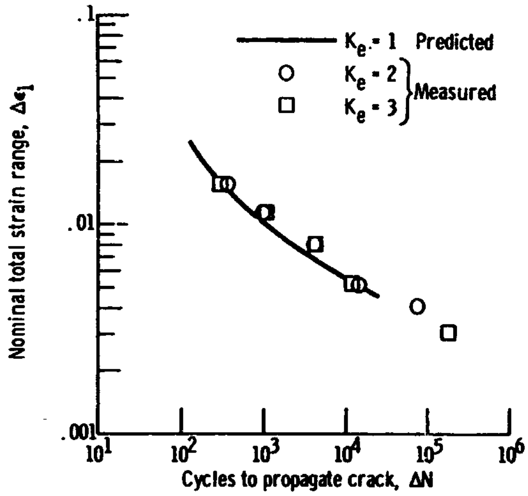

Figure 12. - Crack propagation of notched 7075 T6 aluminum.

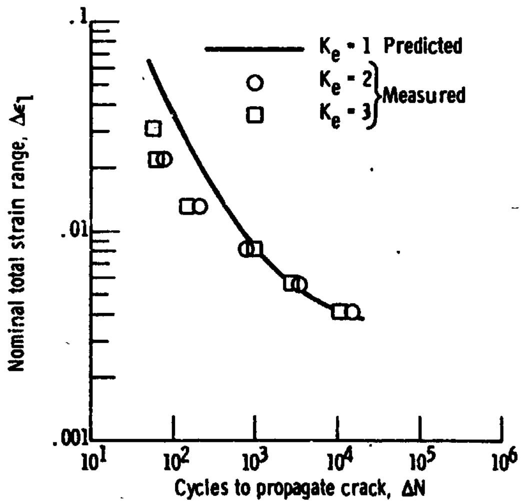

Figure 13. - Crack propagation of annealed AISI 4340 steel.

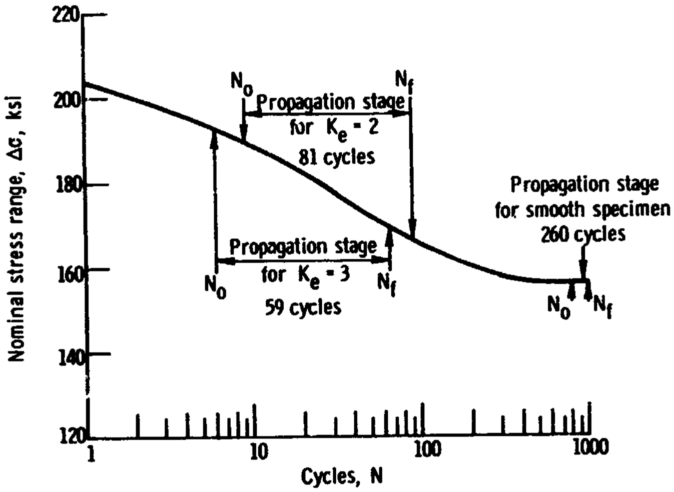

Figure 14. - Variation of stress range with cycles for annealed AISI 4340 steel. $\Delta\epsilon = 0.022$.

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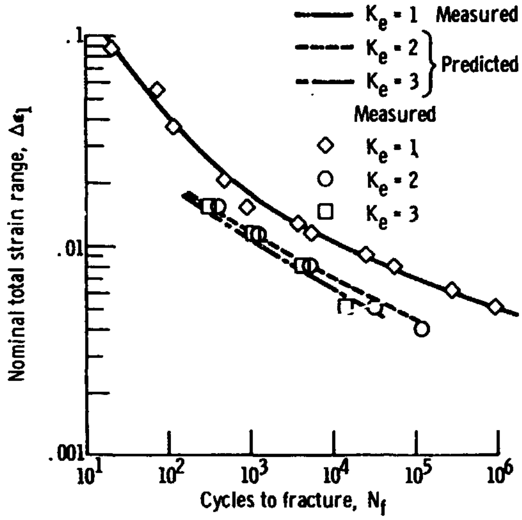

Figure 15. - Axial fatigue of notched 7075 T6 aluminum.

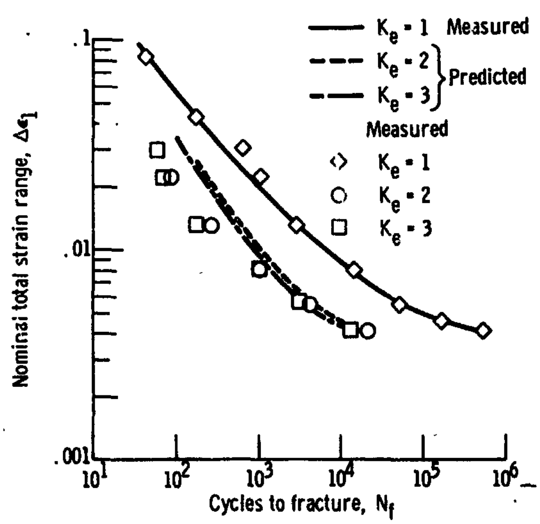

Figure 16. - Axial fatigue of annealed AISI 4340 steel.

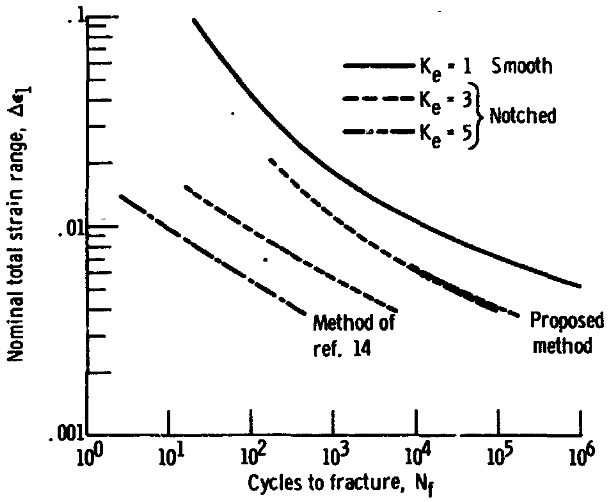

Figure 17. - Comparison of methods for predicting cyclic life of notched specimens for 7075 T6 aluminum.

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